# CHAPTER 4

# RISK-BASED PRGs FOR RADIOACTIVE CONTAMINANTS

This chapter presents standardized exposure parameters, derivations of risk equations, and "reduced" equations for calculating risk-based PRGs for radioactive contaminants for the pathways and land-use scenarios discussed in Chapter 2. In addition, a radiation site case study is provided at the end of the chapter to illustrate (1) how exposure pathways and radionuclides of potential concern (including radioactive decay products) are identified, (2) how initial risk-based PRGs for radionuclides are calculated using reduced equations based on information available at the scoping phase, and (3) how risk-based PRGs can be re-calculated using full risk equations and site-specific data obtained during the baseline risk assessment. Chapters 1 through 3 and Appendices A and B provide the basis for many of the assumptions, equations, and parameters used in this chapter, and therefore should be reviewed before proceeding further into Chapter 4. Also, Chapter 10 in RAGS/HHEM Part A should be consulted for additional guidance on conducting baseline risk assessments at sites contaminated with radioactive substances.

In general, standardized default exposure equations and parameters used to calculate risk-based PRGs for radionuclides are similar in structure and function to those equations and parameters developed in Chapter 3 for nonradioactive chemical carcinogens. Both types of risk equations:

- Calculate risk-based PRGs for each carcinogen corresponding to a pre-specified target cancer risk level of $10^{-6}$. As mentioned in Section 2.8, target risk levels may be modified after the baseline risk assessment based on site-specific exposure conditions, technical limitations, or other uncertainties, as well as on the nine remedy selection criteria specified in the NCP.

- Use standardized default exposure parameters consistent with OSWER Directive 9285.6-03 (EPA 1991b). Where default parameters are not available in that guidance document, other appropriate reference values are used and cited.

- Incorporate pathway-specific default exposure factors that generally reflect RME conditions.

There are, however, several important areas in which risk-based PRG equations and assumptions for radioactive contaminants differ substantially from those used for chemical contaminants. Specifically, unlike chemical equations, risk equations for radionuclides:

- Accept input quantities in units of activity (e.g., picocuries (pCi)) rather than in units of mass (e.g., milligrams (mg)). Activity units are more appropriate for radioactive substances because concentrations of radionuclides in sample media are determined by direct physical measurements of the activity of each nuclide present, and because adverse human health effects due to radionuclide intake or exposure are directly related to the amount, type, and energy of the radiation deposited in specific body tissues and organs.

- Consider the carcinogenic effects of radionuclides only. EPA designates all radionuclides as Class A carcinogens based on their property of emitting ionizing radiation and on the extensive weight of epidemiological evidence of radiation-induced cancer in humans. At most CERCLA radiation sites, potential health risks are usually based on the radiotoxicity, rather than the chemical toxicity, of each radionuclide present.

- Use cancer slope factors that are best estimates (i.e., median or 50th percentile values) of the age-averaged, lifetime excess total cancer risk per unit intake of a radionuclide (e.g., per pCi inhaled or ingested) or per unit external radiation exposure (e.g., per microRoentgen) to gamma-emitting radionuclides. Slope factors given in IRIS and HEAST have been calculated for individual radionuclides based on their unique chemical, metabolic, and radiological properties and using a non-threshold, linear dose-response model. This model accounts for the amount of each radionuclide absorbed into the body from the gastrointestinal tract (by ingestion) or through the lungs (by inhalation), the distribution and retention of each radionuclide in body tissues and organs, as well as the age, sex, and weight of an individual at the time of exposure. The model then averages the risk over the lifetime of that exposed individual (i.e., 70 years). Consequently, radionuclide slope factors are not expressed as a function of body weight or time, and do not require corrections for gastrointestinal absorption or lung transfer efficiencies.

Risk-based PRG equations for radionuclides presented in the following sections of this chapter are derived initially by determining the total risk posed by each radioactive contaminant in a given pathway, and then by rearranging the pathway equation to solve for an activity concentration set equal to a target cancer risk level of $10^{-6}$. At the scoping phase, these equations are "reduced" — and risk-based PRGs are calculated for each radionuclide of concern — using standardized exposure assumptions for each exposure route within each pathway and land-use combination. After the baseline risk assessment, PRGs can be recalculated using full risk equations and site-specific exposure information obtained during the RI.

## 4.1 RESIDENTIAL LAND USE

### 4.1.1 GROUND WATER OR SURFACE WATER

Under the residential land-use scenario, risk from ground-water or surface water radioactive contaminants is assumed to be due primarily to direct ingestion and inhalation of volatile radionuclides released from the water to indoor air. However, because additional exposure routes (e.g., external radiation exposure due to immersion) are possible at some sites for some radionuclides, while only one exposure route may be relevant at others, the risk assessor always should consider all relevant exposure routes and add or modify exposure routes as appropriate.

In the case illustrated below, risks from the two default exposure routes are combined, as follows:

| | | |
|---|---|---|
| Total risk from water | = | Risk from ingestion of radionuclides in water (adult) |
| | + | Risk from indoor inhalation of volatile radionuclides released from water (adult) |

At the scoping phase, risk from indoor inhalation of volatile radionuclides is assumed to be relevant only for radionuclides with a Henry's Law constant of greater than 1 x $10^{-5}$ atm-$m^3$/mole and a molecular weight of less than 200 g/mole. However, radionuclides that do not meet these criteria also may, under certain site-specific water-use conditions, be volatilized into the air from water, and thus pose significant site risks (and require risk-based goals). Therefore, the ultimate decision regarding which contaminants should be considered must be made by the risk assessor on a site-specific basis following completion of the baseline risk assessment.

Total carcinogenic risk is calculated for each radionuclide separately by combining its appropriate oral and inhalation SFs with the two exposure pathways for water, as follows:

| | | | |
|---|---|---|---|
| Total risk | = | $SF_o$ x | Intake from ingestion of of radionuclides |
| | + | $SF_i$ x | Intake from inhalation of volatile radionuclides |

By including appropriate exposure parameters for each type of intake, rearranging and combining exposure terms in the total risk equation, and setting the target cancer risk level equal to $10^{-6}$, the risk-based PRG equation is derived as shown in Equation (10).

Equation (10′), presented in the next box, is the reduced version of Equation (10) based on the standard default values listed below. It is used to calculate risk-based PRGs for radionuclides in water at a pre-specified cancer risk level of $10^{-6}$ by combining each radionuclide's toxicity data with the standard default values for residential land-use exposure parameters.

After the baseline risk assessment, the risk assessor may choose to modify one or more of the exposure parameter default values or assumptions

**RADIONUCLIDE PRGs: RESIDENTIAL WATER — CARCINOGENIC EFFECTS**

Total risk $= [SF_o \times RW \times IR_w \times EF \times ED] + [SF_i \times RW \times K \times IR_a \times EF \times ED]$

$$RW\ (\text{pCi/L; risk-based}) = \frac{TR}{EF \times ED \times [(SF_o \times IR_w) + (SF_i \times K \times IR_a)]} \quad (10)$$

where:

| Parameters | Definition (units) | Default Value |
|---|---|---|
| RW | radionuclide PRG in water (pCi/L) | — |
| TR | target excess individual lifetime cancer risk (unitless) | $10^{-6}$ |
| $SF_i$ | inhalation slope factor (risk/pCi) | radionuclide-specific |
| $SF_o$ | oral (ingestion) slope factor (risk/pCi) | radionuclide-specific |
| EF | exposure frequency (days/yr) | 350 days/yr |
| ED | exposure duration (yr) | 30 yr |
| $IR_a$ | daily indoor inhalation rate ($m^3$/day) | 15 $m^3$/day |
| $IR_w$ | daily water ingestion rate (L/day) | 2 L/day |
| K | volatilization factor (unitless) | 0.0005 x 1000 L/$m^3$ (Andelman 1990) |

**REDUCED EQUATION FOR RADIONUCLIDE PRGs:**
**RESIDENTIAL WATER — CARCINOGENIC EFFECTS**

$$\text{Risk-based PRG}\ (\text{pCi/L; } TR = 10^{-6}) = \frac{9.5 \times 10^{-11}}{2(SF_o) + 7.5(SF_i)} \quad (10')$$

where:

$SF_o$ = oral (ingestion) slope factor (risk/pCi)
$SF_i$ = inhalation slope factor (risk/pCi)

in the risk equations to reflect site-specific conditions. In this event, radionuclide PRGs should be calculated using Equation (10) instead of Equation (10′).

### 4.1.2 SOIL

Under residential land-use conditions, risk from radionuclides in soil is assumed to be due to direct ingestion and external exposure to gamma radiation. Soil ingestion rates differ for children and adults, therefore age-adjusted ingestion rate factors are used in the soil pathway equation. Calculation of the risk from the external radiation exposure route assumes that any gamma-emitting radionuclide in soil is uniformly distributed in that soil within a finite soil depth and density, and dispersed in an infinite plane geometry.

The calculation of external radiation exposure risk also includes two additional factors, the gamma shielding factor ($S_e$) and the gamma exposure time factor ($T_e$), which can be adjusted to account for both attenuation of radiation fields due to shielding (e.g., by structures, terrain, or engineered barriers) and for exposure times of less than 24-hours per day, respectively. $S_e$ is expressed as a fractional value between 0 and 1, delineating the possible risk reduction range from 0% to 100%, respectively, due to shielding. The default value of 0.2 for $S_e$ for both residential and commercial/industrial land-use scenarios reflects the initial conservative assumption of a 20% reduction in external exposure due to shielding from structures (see EPA 1981). $T_e$ is expressed as the quotient of the daily number of hours an individual is exposed directly to an external radiation field divided by the total number of exposure hours assumed each day for a given land-use scenario (i.e., 24 hours for residential and 8 hours for commercial/industrial). The default value of 1 for $T_e$ for both land-use scenarios reflects the conservative assumptions of a 24-hr exposure duration for residential populations (i.e., 24/24 = 1) and an 8-hr exposure duration for workers (i.e., 8/8 = 1). Values for both factors can (and, if appropriate, should) be modified by the risk assessor based on site-specific conditions.

In addition to direct ingestion of soil contaminated with radionuclides and exposure to external radiation from gamma-emitting radionuclides in soil, other soil exposure routes are possible, such as inhalation of resuspended radioactive particles, inhalation of volatile radionuclides, or ingestion of foodcrops contaminated by root or leaf uptake. The risk assessor should therefore identify all relevant exposure routes within the soil pathway and, if necessary, develop equations for risk-based PRGs that combine these exposure routes.

In the case illustrated below, the risk-based PRG is derived to be protective for exposure from the direct ingestion and external radiation routes. Total risk from soil due to ingestion and external radiation is calculated as follows:

| | | |
|---|---|---|
| Total risk from soil | = | Risk from direct ingestion of radionuclides in soil (child to adult) |
| | + | Risk from external radiation from gamma-emitting radionuclides in soil |

Total risk for carcinogenic effects from each radionuclide of potential concern is calculated by combining the appropriate oral slope factor, $SF_o$, with the total radionuclide intake from soil, plus the appropriate external radiation slope factor, $SF_e$, with the radioactivity concentration in soil:

| | | | | |
|---|---|---|---|---|
| Total risk | = | $SF_o$ | x | Intake from direct ingestion of soil |
| | + | $SF_e$ | x | Concentration of gamma-emitting radionuclides in soil |

Adding appropriate parameters, then combining and rearranging the equation to solve for concentration, results in Equation (11).

Equation (11′) is the reduced version of Equation (11) based on the standard default values listed below. Risk-based PRGs for radionuclides in soil are calculated for a pre-specified cancer risk level of $10^{-6}$.

The age-adjusted soil ingestion factor ($IF_{soil/adj}$) used in Equation (11) takes into account the difference in soil ingestion for two exposure groups — children of one to six years and all other individuals from seven to 31 years. $IF_{soil/adj}$ is calculated for radioactive contaminants as shown in Equation (12). Section 3.1.2 provides additional discussion on the age-adjusted soil ingestion factor.

If any parameter values or exposure assumptions are adjusted after the baseline risk assessment to reflect site-specific conditions, soil PRGs should be calculated using Equation (11).

## 4.2 COMMERCIAL/INDUSTRIAL LAND USE

### 4.2.1 WATER

Under the commercial/industrial land use scenario, risk-based PRGs for radionuclides in ground water (and for radionuclides in surface water used for drinking water purposes) are based on residential exposures and calculated according to the procedures detailed in Section 4.1.1 (see Section 3.2.1 for the rationale for this approach). Risk-based PRGs should be calculated considering the possibility that both the worker and general population at large may be exposed to the same contaminated water supply.

### 4.2.2 SOIL

Under the commercial/industrial land use scenario, four soil exposure routes — direct ingestion, inhalation of volatile radionuclides, inhalation of resuspended radioactive particulates, and external exposure due to gamma-emitting radionuclides — are combined to calculate risk-based radionuclide PRGs in soil for adult worker exposures. Additional exposure routes (e.g., ingestion of foodcrops contaminated by radionuclide uptake) are possible at some sites, while only one exposure route (e.g., external radiation exposure only) may be relevant at others. The risk assessor should therefore consider and combine all relevant soil exposure routes, as necessary and appropriate, based on site-specific conditions.

**RADIONUCLIDE PRGs: RESIDENTIAL SOIL — CARCINOGENIC EFFECTS**

$$\text{Total risk} = RS \times [(SF_o \times 10^{-3} g/mg \times EF \times IF_{soil/adj}) + (SF_e \times 10^{3} g/kg \times ED \times D \times SD \times (1-S_e) \times T_e)]$$

$$\text{RS (pCi/g; risk-based)} = \frac{TR}{(SF_o \times 10^{-3} \times EF \times IF_{soil/adj}) + (SF_e \times 10^{3} \times ED \times D \times SD \times (1-S_e) \times T_e)} \quad (11)$$

where:

| Parameters | Definition (units) | Default Value |
|---|---|---|
| RS | radionuclide PRG in soil (pCi/g) | — |
| TR | target excess individual lifetime cancer risk (unitless) | $10^{-6}$ |
| $SF_o$ | oral (ingestion) slope factor (risk/pCi) | radionuclide-specific |
| $SF_e$ | external exposure slope factor (risk/yr per pCi/m$^2$) | radionuclide-specific |
| EF | exposure frequency (days/yr) | 350 days/yr |
| ED | exposure duration (yr) | 30 yr |
| $IF_{soil/adj}$ | age-adjusted soil ingestion factor (mg-yr/day) | 3600 mg-yr/day (see Equation (12)) |
| D | depth of radionuclides in soil (m) | 0.1 m |
| SD | soil density (kg/m$^3$) | $1.43 \times 10^3$ kg/m$^3$ |
| $S_e$ | gamma shielding factor (unitless) | 0.2 (see Section 4.1.2) |
| $T_e$ | gamma exposure time factor (unitless) | 1 (see Section 4.1.2) |

**REDUCED EQUATION FOR RADIONUCLIDE PRGs: RESIDENTIAL SOIL — CARCINOGENIC EFFECTS**

$$\text{Risk-based PRG (pCi/g; TR} = 10^{-6}) = \frac{1 \times 10^{-6}}{1.3 \times 10^{3} (SF_o) + 3.4 \times 10^{6} (SF_e)} \quad (11')$$

where:

$SF_o$ = oral (ingestion) slope factor (risk/pCi)
$SF_e$ = external exposure slope factor (risk/yr per pCi/m$^2$)

**AGE-ADJUSTED SOIL INGESTION FACTOR**

$$IF_{soil/adj} \text{ (mg-yr/day)} = (IR_{soil/age\ 1\text{-}6} \times ED_{age\ 1\text{-}6}) + (IR_{soil/age\ 7\text{-}31} \times ED_{age\ 7\text{-}31}) \quad (12)$$

where:

| Parameters | Definition (units) | Default Value |
|---|---|---|
| $IF_{soil/adj}$ | age-adjusted soil ingestion factor (mg-yr/day) | 3600 mg-yr/day |
| $IR_{soil/age\ 1\text{-}6}$ | ingestion rate of soil ages 1-6 (mg/day) | 200 mg/day |
| $IR_{soil/age\ 7\text{-}31}$ | ingestion rate of soil ages 7-31 (mg/day) | 100 mg/day |
| $ED_{age\ 1\text{-}6}$ | exposure duration during ages 1-6 (yr) | 6 yr |
| $ED_{age\ 7\text{-}31}$ | exposure duration during ages 7-31 (yr) | 24 yr |

In the case illustrated below, total risk from radionuclides in soil is calculated as the summation of the individual risks from each of the four exposure routes listed above:

| | | |
|---|---|---|
| Total risk from soil | = | Risk from direct ingestion of radionuclides in soil (worker) |
| | + | Risk from inhalation of volatile radionuclides (worker) |
| | + | Risk from inhalation of resuspended radioactive particulates (worker) |
| | + | Risk from external radiation from gamma-emitting radionuclides (worker) |

Total risk for carcinogenic effects for each radionuclide is calculated by combining the appropriate ingestion, inhalation, and external exposure SF values with relevant exposure parameters for each of the four soil exposure routes as follows:

| | | | |
|---|---|---|---|
| Total risk | = | $SF_o$ x | Intake from direct ingestion of radionuclides in soil (worker) |
| | + | $SF_i$ x | Intake from inhalation of volatile radionuclides (worker) |
| | + | $SF_i$ x | Intake from inhalation of resuspended radioactive particulates (worker) |
| | + | $SF_e$ x | Concentration of gamma-emitting radionuclides in soil (worker) |

Adding appropriate parameters, and then combining and rearranging the equation to solve for concentration, results in Equation (13).

Equation (13′) below is the reduced version of Equation (13) based on the standard default values below and a pre-specified cancer risk level of $10^{-6}$. It combines the toxicity information of a radionuclide with standard exposure parameters for commercial/industrial land use to generate the concentration of that radionuclide corresponding to a $10^{-6}$ carcinogenic risk level due to that radionuclide.

If any parameter default values or assumptions are changed after the baseline risk assessment to reflect site-specific conditions, radionuclide soil PRGs should be derived using Equation (13).

### 4.2.3 SOIL-TO-AIR VOLATILIZATION FACTOR

The VF, defined in Section 3.3.1 for chemicals, also applies for radioactive contaminants with the following exceptions.

- Most radionuclides are heavy metal elements and are non-volatile under normal, ambient conditions. For these radionuclides, VF values need not be calculated and the risk due to the inhalation of volatile forms of these nuclides can be ignored for the purposes of determining PRGs.

- A few radionuclides, such as carbon-14 (C-14), tritium (H-3), phosphorus-32 (P-32), sulfur-35 (S-35), and other isotopes, are volatile under certain chemical or environmental conditions, such as when they are combined chemically with volatile organic compounds (i.e., the so-called radioactively-labeled or "tagged" organic compounds), or when they can exist in the environment in a variety of physical forms, such as C-14 labeled carbon dioxide ($CO_2$) gas and tritiated water vapor. For these radionuclides, VF values should be calculated using the Hwang and Falco (1986) equation provided in Section 3.3.1 based on the chemical species of the compound with which they are associated.

- The naturally occurring, non-volatile radioisotopes of radium, namely Ra-226 and Ra-224, undergo radioactive decay and form inert, gaseous isotopes of radon, i.e., Rn-222 (radon) and Rn-220 (thoron), respectively. Radioactive radon and thoron gases emanate from their respective parent radium isotopes in soil, escape into the air, and can pose cancer risks if inhaled. For Ra-226 and Ra-224 in soil, use the default values shown in the box on page 40 for VF and for $SF_i$ in Equation (12) and Equation (12′).

## 4.3 RADIATION CASE STUDY

This section presents a case study of a hypothetical CERCLA radiation site, the ACME Radiation Co. site, to illustrate the process of calculating pathway-specific risk-based PRGs for radionuclides using the risk equations and assumptions presented in the preceding sections of this chapter. The radiation site case study is modeled after the XYZ Co. site study discussed in

**RADIONUCLIDE PRGs: COMMERCIAL/INDUSTRIAL SOIL — CARCINOGENIC EFFECTS**

$$\text{Total risk} = RS \times ED \times [(SF_o \times 10^{-3}g/mg \times EF \times IR_{soil}) + (SF_i \times 10^3 g/kg \times EF \times IR_{air} \times 1/VF) + (SF_i \times 10^3 g/kg \times EF \times IR_{air} \times 1/PEF) + (SF_e \times 10^3 g/kg \times D \times SD \times (1-S_e) \times T_e)]$$

$$RS \ (pCi/g; \text{risk-based}) = \frac{TR}{ED \times [(SF_o x10^{-3} xEFxIR_{soil}) + (SF_i x10^3 xEFxIR_{air}) \times (1/VF + 1/PEF) + (SF_e x10^3 xDxSDx(1-S_e)xT_e)]} \quad (13)$$

where:

| Parameters | Definition (units) | Default Value |
|---|---|---|
| RS | radionuclide PRG in soil (pCi/g) | — |
| TR | target excess individual lifetime cancer risk (unitless) | $10^{-6}$ |
| $SF_i$ | inhalation slope factor (risk/pCi) | radionuclide-specific |
| $SF_o$ | oral (ingestion) slope factor (risk/pCi) | radionuclide-specific |
| $SF_e$ | external exposure slope factor (risk/yr per pCi/m$^2$) | radionuclide-specific |
| EF | exposure frequency (days/yr) | 250 days/yr |
| ED | exposure duration (yr) | 25 yr |
| $IR_{air}$ | workday inhalation rate of air (m$^3$/day) | 20 m$^3$/day |
| $IR_{soil}$ | daily soil ingestion rate (mg/day) | 50 mg/day |
| VF | soil-to-air volatilization factor (m$^3$/kg) | radionuclide-specific (see Section 4.2.3) |
| PEF | particulate emission factor (m$^3$/kg) | $4.63 \times 10^9$ m$^3$/kg (see Section 3.3.2) |
| ✓D | depth of radionuclides in soil (m) | 0.1 m |
| ✓SD | soil density (kg/m$^3$) | $1.43 \times 10^3$ kg/m$^3$ |
| ✓$S_e$ | gamma shielding factor (unitless) | 0.2 (see Section 4.1.2) |
| ✓$T_e$ | gamma exposure factor (unitless) | 1 (see Section 4.1.2) |

**REDUCED EQUATION FOR RADIONUCLIDE PRGs:**
**COMMERCIAL/INDUSTRIAL SOIL — CARCINOGENIC EFFECTS***

$$\text{Risk-based PRG } (pCi/g;\ TR = 10^{-6}) = \frac{1 \times 10^{-6}}{[(3.1 \times 10^2 (SF_o)) + ((1.3 \times 10^8/VF + 2.7 \times 10^{-2})(SF_i)) + (2.9 \times 10^6 (SF_e))]} \quad (13')$$

where:

$SF_o$ = oral (ingestion) slope factor (risk/pCi)
$SF_i$ = inhalation slope factor (risk/pCi)
$SF_e$ = external exposure slope factor (risk/yr per pCi/m$^2$)
VF = radionuclide-specific soil-to-air volatilization factor in m$^3$/kg (see Section 3.3.1)

*NOTE: See Section 4.2.3 when calculating PRGs for Ra-226 and Ra-224.

Chapters 2 and 3. It generally follows a two-phase format which consists of a "at the scoping stage" phase wherein risk-based PRGs for radionuclides of potential concern are calculated initially using reduced equations based on PA/SI data, and then a second, "after the baseline risk assessment" phase wherein radionuclide PRGs are recalculated using full equations and modified site-specific parameter values based on RI/FS data.

Following an overview of the history and current status of the site presented in Section 4.3.1, Section 4.3.2 covers a number of important steps taken early in the scoping phase to calculate preliminary risk-based PRGs assuming a specific

**SOIL DEFAULT VALUES FOR VF AND SF, FOR Ra-226 AND Ra-224**

| Radium | Default VF Value $\left(\frac{pCi/kg\ Ra}{pCi/m^3\ Rn^*}\right)$ | Inhalation Slope Factor, $SF_i$ (risk/pCi)** |
|---|---|---|
| Ra-226 | 8 | 1.1E-11 |
| Ra-224 | 200 | 4.7E-11 |

* Calculated using values taken from NCRP 1976 and UNSCEAR 1982: Assumptions: (1) an average Ra-226 soil concentration of 1 pCi/g associated with an average ambient Rn-222 air concentration of 120 pCi/$m^3$ and (2) an average Ra-224 soil concentration of 1 pCi/g associated with an average ambient Rn-220 air concentration of 5 pCi/$m^3$.

** Slope factor values are for Rn-222 (plus progeny) and for Rn-220 (plus progeny).

land-use scenario. Section 4.3.3 then discusses how initial assumptions and calculations can be modified when additional site-specific information becomes available.

### 4.3.1 SITE HISTORY

The ACME Radiation Co. site is an abandoned industrial facility consisting of a large factory building situated on ten acres of land surrounded by a high-density residential neighborhood. Established in 1925, the ACME Co. manufactured luminous watch dials and gauges using radium-based paint and employed approximately 100 workers, mostly women. With the declining radium market, ACME phased out dial production and expanded its operations in 1960 to include brokering (collection and disposal) of low-level radioactive waste (LLW). After the company was issued a state license in 1961, ACME began receiving LLW from various nearby hospitals and research laboratories. In 1975, acting on an anonymous complaint of suspected mishandling of radioactive waste, state officials visited the ACME Co. site and cited the company for numerous storage and disposal violations. After ACME failed to rectify plant conditions identified in initial and subsequent citations, the state first suspended, and then later revoked its operating license in 1978. Around the same time, officials detected radium-226 (Ra-226) contamination at a few neighboring locations off site. However, no action was taken against the company at that time. When ACME filed for bankruptcy in 1985, it closed its facility before completing cleanup.

In 1987, the state and EPA conducted an aerial gamma survey over the ACME Radiation Co. site and surrounding properties to investigate the potential extent of radioactive contamination in these areas. The overflight survey revealed several areas of elevated exposure rate readings, although individual gamma-emitting radionuclides could not be identified. When follow-up ground level surveys were performed in 1988, numerous "hot spots" of Ra-226 were pinpointed at various locations within and around the factory building. Three large soil piles showing enhanced concentrations of Ra-226 were discovered along the southern border. Approximately 20 rusting drums labelled with LLW placards also were discovered outside under a covered storage area. Using ground-penetrating radar, EPA detected subsurface magnetic anomalies in a few locations within the property boundary which suggested the possibility of buried waste drums. Based on interviews with people living near the site and with former plant workers, the state believes that radium contaminated soil may have been removed from the ACME site in the past and used locally as fill material for the construction of new homes and roadbeds. Site access is currently limited (but not entirely restricted) by an existing security fence.

In 1988, EPA's regional field investigation team completed a PA/SI. Based on the PA/SI data, the ACME Radiation Co. site scored above 28.50 using the HRS and was listed on the National Priorities List in 1989. Early in 1990, an RI/FS was initiated and a baseline risk assessment is currently in progress.

### 4.3.2 AT THE SCOPING PHASE

In this subsection, several steps are outlined to show by example how initial site data are used at the scoping phase to calculate risk-based PRGs for radionuclides in specific media of concern. Appropriate sections of Chapters 2 and 3 should be consulted for more detailed explanations for each step considered below.

**Identify Media of Concern.** A large stream runs along the western border of the site and feeds into a river used by some of the local residents for fishing and boating. Supplemental water intake ducts for the municipal water treatment plant are located approximately 300 yards downriver, and the site is situated over an aquifer which serves as the primary drinking water supply for a community of approximately 33,000 people.

Analyses of ground water, soil, and stream sediment samples taken during the PA/SI revealed significant levels of radionuclide contamination. Potential sources of contamination include the soil piles, process residues in soil, and radionuclides leaking from buried drums. Air filter samples and surface water samples from the stream and river showed only background levels of activity. (Background concentrations were determined from analyses conducted on a limited number of air, ground water, surface water, and soil samples collected approximately one mile from the site.)

The data show that the media of potential concern at this site include ground water and soil. Although stream water and river water were not found to be contaminated, both surface water bodies may become contaminated in the future due to the migration of radionuclides from sediment, from the exposed soil piles, or from leaking drums. Thus, surface water is another medium of potential concern.

For simplicity, only soil will be discussed as the medium of concern during the remainder of this case study. Procedures discussed for this medium can nevertheless be applied in a similar manner to all other media of concern.

**Identify Initial List of Radionuclides of Concern.** The PA/SI for the ACME Radiation Co. site identified elevated concentrations of five radionuclides in soil (Ra-226, tritium (H-3), carbon-14 (C-14), cesium (Cs-137), and strontium (Sr-90)). These comprise the initial list of radionuclides of potential concern.

Site records indicate that radioisotopes of cobalt (Co-60), phosphorus (P-32), sulfur (S-35), and americium (Am-241 and Am-243) were included on the manifests of several LLW drums in the storage area and on the manifests of other drums suspected to be buried onsite. Therefore, although not detected in any of the initial soil samples analyzed, Co-60, P-32, S-35, Am-241, and Am-243 are added to the list for this medium because of their potential to migrate from leaking buried drums into the surrounding soil.

**Identify Probable Land Uses.** The ACME Radiation Co. site is located in the center of a rapidly developing suburban community comprised of single and multiple family dwellings. The area immediately encircling the site was recently re-zoned for residential use only; existing commercial and light industrial facilities are currently being relocated. Therefore, residential use is determined to be the most reasonable future land use for this site.

**Identify Exposure Pathways, Parameters, and Equations.** During the scoping phase, available site data were neither sufficient to identify all possible exposure pathways nor adequate enough to develop site-specific fate and transport equations and parameters. Therefore, in order to calculate initial risk-based PRGs for radionuclides of potential concern in soil, the standardized default soil exposure equation and assumptions provided in this chapter for residential land use in Section 4.1.2 are selected. (Later in this case study, examples are provided to illustrate how the full risk equation (Equation (11)) and assumptions are modified when baseline risk assessment data become available.)

For the soil pathway, the exposure routes of concern are assumed to be direct ingestion of soil contaminated with radionuclides and exposure to external radiation from gamma-emitting radionuclides. Again, although soil is the only medium discussed throughout this case study, exposure pathways, parameters, equations, and eventually risk-based concentrations would need to be identified and developed for all other media and exposure pathways of potential concern at an actual site.

**Identify Toxicity Information.** To calculate media-specific risk-based PRGs, reference toxicity values for radiation-induced cancer effects are required (i.e., SFs). As stated previously, soil ingestion and external radiation are the exposure routes of concern for the soil pathway. Toxicity information (i.e., oral, inhalation, and external exposure SFs) for all radionuclides of potential concern at the ACME Radiation Co. site are obtained from IRIS or HEAST, and are shown in the box on the following page.

**RADIATION CASE STUDY:**
**TOXICITY INFORMATION FOR RADIONUCLIDES OF POTENTIAL CONCERN***

| Radionuclides | Radioactive Half-life (yr) | Decay Mode | ICRP Lung Classification | Inhalation Slope Factor (risk/pCi) | Ingestion Slope Factor (risk/pCi) | External Exposure Slope Factor (risk/yr per pCi/m$^2$) |
|---|---|---|---|---|---|---|
| H-3 | 12 | beta | g | 7.8E-14 | 5.5E-14 | NA |
| C-14 | 5730 | beta | g | 6.4E-15 | 9.1E-13 | NA |
| P-32 | 0.04 | beta | D | 3.0E-12 | 3.5E-12 | NA |
| S-35 | 0.24 | beta | D | 1.9E-13 | 2.2E-13 | NA |
| Co-60 | 5 | beta/gamma | Y | 1.6E-10 | 1.5E-11 | 1.3E-10 |
| Sr-90 | 29 | beta | D | 5.6E-11 | 3.3E-11 | NA |
| Cs-137 | 30 | beta | D | 1.9E-11 | 2.8E-11 | NA |
| Ra-226 | 1600 | alpha/gamma | W | 3.0E-09 | 1.2E-10 | 4.2E-13 |
| Am-241 | 432 | alpha/gamma | W | 4.0E-08 | 3.1E-10 | 1.6E-12 |
| Am-243 | 7380 | alpha/gamma | W | 4.0E-08 | 3.1E-10 | 3.6E-12 |

* Sources: HEAST and Federal Guidance Report No. 11. All information in this example is for illustration only.

NA = Not applicable (i.e., these radionuclides are not gamma-emitters and the direct radiation exposure pathway can be ignored).

**Calculate Risk-based PRGs.** At this step, risk-based PRGs are calculated for each radionuclide of potential concern using the reduced risk Equation (11′) in Section 4.1.2, SF values obtained from IRIS and HEAST, and standardized default values for parameters for the residential land-use scenario. To calculate the risk-based PRG for Co-60 at a pre-specified target risk level of $10^{-6}$, for example, its ingestion SF of $1.5 \times 10^{-11}$ and its external exposure SF of $1.3 \times 10^{-10}$ are substituted into Equation (11′), along with the standardized default values, as follows:

$$\text{Risk-based PRG for Co-60 (pCi/g; TR} = 10^{-6}) = \frac{1 \times 10^{-6}}{1.3 \times 10^{3}(SF_o) + 3.4 \times 10^{6}(SF_e)}$$

where:

$SF_o$ = oral (ingestion) slope factor for Co-60 = $1.5 \times 10^{-11}$ (risk/pCi)

$SF_e$ = external exposure slope factor for Co-60 = $1.3 \times 10^{-10}$ (risk/yr per pCi/m²)

Substituting the values for $SF_o$ and $SF_e$ for Co-60 into Equation (11′) results in:

Risk-based PRG for Co-60 (pCi/g; TR = $10^{-6}$) =

$$\frac{1 \times 10^{-6}}{[(1.3 \times 10^{3})(1.5 \times 10^{-11}) + (3.4 \times 10^{6})(1.3 \times 10^{-10})]}$$

= 0.002 pCi of Co-60/g of soil

In a similar manner, risk-based PRGs can be calculated for all other radionuclides of concern in soil at the ACME Radiation Co. site. These PRGs are presented in the next box.

**RADIATION CASE STUDY: INITIAL RISK-BASED PRGs FOR RADIONUCLIDES IN SOIL***

| Radionuclides | Risk-based Soil PRG (pCi/g) |
|---|---|
| H-3 | 14,000 |
| Sr-90 (only) | 23 |
| P-32 | 220 |
| S-35 | 3,500 |
| C-14 | 850 |
| Co-60 | 0.002 |
| Cs-137 (only) | 27 |
| Ra-226 (only) | 0.6 |
| Am-241 | 0.2 |
| Am-243 (only) | $7.9 \times 10^{-2}$ |

* Calculated for illustration only using Equation (11′) in Section 4.1.2. Values have been rounded off.

### 4.3.3 AFTER THE BASELINE RISK ASSESSMENT

In this subsection, several steps are outlined which demonstrate how site-specific data obtained during the baseline risk assessment can be used to recalculate risk-based PRGs for radionuclides in soil. Appropriate sections of Chapters 2 and 3 should be consulted for more detailed explanations for each step considered below.

**Review Media of Concern.** During the RI/FS, gamma radiation surveys were conducted in the yards of several homes located within a two-block radius of the ACME Radiation Co. site. Elevated exposure rates, ranging from approximately two to four times the natural background rate, were measured on properties immediately bordering the site. Measurements onsite ranged from 10 to 50 times background. In both cases, enhanced soil concentrations of Ra-226 (and decay products) and several other gamma-emitting radionuclides were discovered to be the sources of these elevated exposure rates. Therefore, soil continues as a medium of potential concern.

**Modify List of Radionuclides of Concern.** During scoping, five radionuclides (Ra-226, H-3, C-14, Cs-137, and Sr-90) were detected in elevated concentrations in soil samples collected at the ACME Radiation Co. site. These made up the initial list of radionuclides of potential concern. Although not detected during the first round of sampling, five additional radionuclides (P-32, S-35, Co-60, Am-241, and Am-243) were added to this list because of their potential to migrate from buried leaking drums into the surrounding soil.

With additional RI/FS data, some radionuclides are now added to the list, while others are dropped. For example, soil analyses failed to detect P-32 (14-day half-life) or S-35 (87-day half-life) contamination. Decay correction calculations strongly suggest that these radionuclides should not be present onsite in detectable quantities after an estimated burial time of 30 years. Therefore, based on these data, P-32 and S-35 are dropped from the list. Soil data also confirm that decay products of Ra-226, Sr-90, Cs-137, and Am-243 (identified in the first box below) are present in secular equilibrium (i.e., equal activity concentrations) with their respective parent isotopes.

Assuming secular equilibrium, slope factors for the parent isotope and each of its decay series members are summed. Parent isotopes are designated with a "+D" to indicate the composite slope factors of its decay chain (shown in bold face in the second box below). Thus, Ra-226+D, Sr-90+D, Cs-137+D, and Am-243+D replace their respective single-isotope values in the list of radionuclides of potential concern, and their composite SFs are used in the full soil pathway equation to recalculate risk-based concentrations.

**RADIATION CASE STUDY: DECAY PRODUCTS**

| Parent Radionuclide | Decay Product(s) (Half-life) |
|---|---|
| Ra-226 | Rn-222 (4 days), Po-218 (3 min), Pb-214 (27 min), Bi-214 (20 min), Po-214 (<1 s), Pb-210 (22 yr), Bi-210 (5 days), Po-210 (138 days) |
| Sr-90 | Y-90 (14 hr) |
| Cs-137 | Ba-137m (2 min) |
| Am-243 | Np-239 (2 days) |

**RADIATION CASE STUDY: SLOPE FACTORS FOR DECAY SERIES[a]**

| | Slope Factors | | |
|---|---|---|---|
| Decay Series | Inhalation | Ingestion | External |
| Ra-226 | 3.0E-09 | 1.2E-10 | 4.2E-13 |
| Rn-222 | 7.2E-13 | — | 2.2E-14 |
| Po-218 | 5.8E-13 | 2.8E-14 | 0.0E+00 |
| Pb-214 | 2.9E-12 | 1.8E-13 | 1.5E-11 |
| Bi-214 | 2.2E-12 | 1.4E-13 | 8.0E-11 |
| Po-214 | 2.8E-19 | 1.0E-20 | 4.7E-15 |
| Pb-210 | 1.7E-09 | 6.5E-10 | 1.8E-13 |
| Bi-210 | 8.1E-11 | 1.9E-12 | 0.0E+00 |
| Po-210 | 2.7E-09 | 2.6E-10 | 4.8E-16 |
| **Ra-226+D** | **7.5E-09** | **1.0E-09** | **9.6E-11** |
| Sr-90 | 5.6E-11 | 3.3E-11 | 0.0E+00 |
| Y-90 | 5.5E-12 | 3.2E-12 | 0.0E+00 |
| **Sr-90+D** | **6.2E-11** | **3.6E-11** | **0.0E+00** |
| Cs-137 | 1.9E-11 | 2.8E-11 | 0.0E+00 |
| Ba-137m | 6.0E-16 | 2.4E-15 | 3.4E-11 |
| **Cs-137+D** | **1.9E-11** | **2.8E-11** | **3.4E-11** |
| Am-243 | 4.0E-08 | 3.1E-10 | 3.6E-12 |
| Np-239 | 1.5E-12 | 9.3E-13 | 1.1E-11 |
| **Am-243+D** | **4.0E-08** | **3.1E-10** | **1.5E-11** |

[a] All information in this example is for illustration purposes only.

**Review Land-use Assumptions.** At this step, the future land-use assumption chosen during scoping is reviewed. Since the original assumption of future residential land use is supported by RI/FS data, it is not modified.

**Modify Exposure Pathways, Parameters, and Equations.** Based on site-specific information, the upper-bound residence time for many of the individuals living near the ACME Radiation Co. site is determined to be 45 years rather than the default value of 30 years. Therefore, the exposure duration parameter used in Equation (11) in Section 4.1.2 is substituted accordingly. It is also determined that individuals living near the site are only exposed to the external gamma radiation field approximately 18 hours each day, and that their homes provide a shielding factor of about 0.5 (i.e., 50%). Therefore, values for $T_e$ and $S_e$ are changed to 0.75 (i.e., 18 hr/24 hr) and 0.5, respectively.

**Modify Toxicity Information.** As discussed above in the section on modifying the list of radionuclides of concern, oral, inhalation, and external exposure slope factors for Ra-226, Sr-90, Cs-137, and Am-243 were adjusted to account for the added risks (per unit intake and/or exposure) contributed by their respective decay series members that are in secular equilibrium.

**Recalculate Risk-based PRGs.** At this step, risk-based PRGs are recalculated for all remaining radionuclides of potential concern using the full risk equation for the soil pathway (i.e., Equation (11)) modified by revised site-specific assumptions regarding exposures, as discussed above.

To recalculate the risk-based PRG for Co-60 at a pre-specified target risk level of $10^{-6}$, for example, its ingestion SF of $1.5 \times 10^{-11}$, and its external exposure SF of $1.3 \times 10^{-10}$ are substituted into Equation (11), along with other site-specific parameters, as shown in the next box.

In a similar manner, risk-based PRGs can be recalculated for all remaining radionuclides of potential concern in soil at the ACME Radiation Co. site. These revised PRGs are presented in the box on the next page. In those cases where calculated risk-based PRGs for radionuclides are below current detection limits, risk assessors should contact the Superfund Health Risk Technical Support Center for additional guidance.

**RADIATION CASE STUDY: REVISED RISK EQUATION FOR RESIDENTIAL SOIL**

RS for Co-60 (pCi/g; risk-based)

$$= \frac{TR}{(SF_o \times 10^{-3} \times EF \times IF_{soil/adj}) + (SF_e \times 10^{3} \times ED \times D \times SD \times (1-S_e) \times T_e)}$$

$$= 0.003 \text{ pCi/g}$$

where:

| Parameters | Definition (units) | Revised Value |
|---|---|---|
| RS | radionuclide PRG in soil (pCi/g) | — |
| TR | target excess individual lifetime cancer risk (unitless) | $10^{-6}$ |
| $SF_o$ | oral (ingestion) slope factor (risk/pCi) | $1.5 \times 10^{-11}$ (risk/pCi) |
| $SF_e$ | external exposure slope factor (risk/yr per pCi/m$^2$) | $1.3 \times 10^{-10}$ (risk/yr per pCi/m$^2$) |
| EF | exposure frequency (days/yr) | 350 days/yr |
| ED | exposure duration (yr) | 45 yr |
| $IF_{soil/adj}$ | age-adjusted soil ingestion factor (mg-yr/day) | 5100 mg-yr/day |
| D | depth of radionuclides in soil (m) | 0.1 m |
| SD | soil density (kg/m$^3$) | $1.43 \times 10^3$ kg/m$^3$ |
| $S_e$ | gamma shielding factor (unitless) | 0.5 |
| $T_e$ | gamma exposure time factor (unitless) | 0.75 |

(Note: To account for the revised upper-bound residential residency time of 45 years, the age-adjusted soil ingestion factor was recalculated using the equation in Section 4.1.2 and an adult exposure duration of 39 years for individuals 7 to 46 years of age.)

**RADIATION CASE STUDY:**
**REVISED RISK-BASED PRGs FOR RADIONUCLIDES IN SOIL***

| Radionuclides | Risk-based Soil PRG (pCi/g) |
|---|---|
| H-3 | 10,200 |
| Sr-90+D | 20 |
| C-14 | 620 |
| Co-60 | 0.003 |
| Cs-137+D | 0.01 |
| Ra-226+D | 0.004 |
| Am-241 | 0.2 |
| Am-243+D | 0.03 |

* Calculated for illustration only. Values have been rounded off.